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A new control strategy of solid oxide fuel cell based on coordination between hydrogen fuel flow rate and utilization factor

Majid Nayeripour [a,*], Mohammad Hoseintabar [b]

[a] Faculty of Electrical and Electronic Engineering, Shiraz University of Technology, Shiraz, Iran
[b] Faculty of Electrical and Electronic Engineering, Al-Taha University, Tehran, Iran

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ABSTRACT

In this paper, a new control strategy for rapid changing of output power level of solid oxide fuel cell (SOFC) power plant is proposed based on the adaptive control strategy. In the proposed control strategy, the utilization factor (UF) of solid oxide fuel cell stack is kept constant in steady state by feeding hydrogen to the stack at its rate value. In transient state, the utilization factor of the stack changes in its allowable range by controlling the current drawn and power condition unit. This coordination returns the utilization factor of fuel cell (FC) system to its optimal value. The proposed control strategy will be very useful to protect SOFC stack from internal damage during large disturbances. In order to investigate the proposed control strategy and verify dynamic modeling, the MATLAB/SIMULIK software is used. The results show the capability of the proposed control strategy under rapid changes in load demand.

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1. Introduction

The ever increasing energy consumption, global warming, and oil price over the last decades, have attracted more attentions to utilize alternative energy sources instead of conventional power generation systems. FC-based power generation systems are emerging as promising alternative power generation systems because of their high efficiency, low environmental impact, modularity and high reliability. FCs are classified based on different features such as temperature or electrolyte. With respect to the electrolyte classification, the FCs systems are classified as electrolyte types such as phosphoric acids (PAFC), molten carbonate (MCFC), solid oxide (SOFC) and proton exchange membrane (PEMFC). Among them the PEMFC type is widely used in different applications such as portable or residential applications due to its low temperature, high power density and relatively short start up time. However, this type of FC system needs pure hydrogen as fuel to operate normally and have lower efficiency against high temperature SOFC [1].

SOFC produces direct current (DC) electric power through an electrochemical process. The electrolyte of the SOFC is solid and

* Corresponding author.
E-mail addresses: nayeri@sutech.ac.ir, mnayeri@yahoo.com (M. Nayeripour), mohammad.hoseintabar@gmail.com, M.hoseintabar@ut.ac.ir (M. Hoseintabar).

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Nomenclature

E_0	Ideal standard potential
F	Faraday's constant
I_{fc}	Fuel cell current
K_{an}	Anode valve constant
K_{H_2}	Valve molar constant for hydrogen
K_{H_2O}	Valve molar constant for water
K_{O_2}	Valve molar constant for oxygen
K_r	Constant $(=N_0/4F)$
M_{H_2}	Molecular mass of hydrogen
n_{H_2}	Number of hydrogen moles in the anode channel
N_0	Number of cells in series in the stack
p_i	Partial pressure
$q_{H_2}^{in}$	Input fuel flow
$q_{H_2}^{o}$	Output fuel flow
$q_{H_2}^{r}$	Fuel flow that reacts
R	Ohmic loss
R_{H-O}	Ratio of hydrogen to oxygen
R	Universal gas constant
T	Absolute temperature
U	Fuel utilization factor
V_{an}	Volume of anode
V_{fc}	Fuel cell voltage
τ_{H_2}	Response time for hydrogen flow
τ_{H_2O}	Response time for water flow
τ_{O_2}	Response time for oxygen flow

operates at high temperatures (600 °C to 1000 °C). Due to high temperature, SOFC can produce electricity from natural gases with no additional reforming catalysts needed. The output voltage of SOFC depends on fuel flow, oxidant flow, temperature, and load demand. In addition, this kind of FC system has a simple structure and internal reforming capability [2].

FCs power generation systems have slow transient (dynamic) response than the dynamic response of the power condition unit that they are connected. The FC's inability to change its current as fast as the electrical load changes has important implications on the overall power system design that should be considered [3]. Various types of modeling, control, and performance analysis of FC system in different applications have been proposed in the recent decade. A summary for SOFC system modeling and its control strategy in the recent decade is expressed in Table 1 [2,4–11].

In this paper, the simplified model of power electronics interfacing components are considered and also the effects of ripples generated due to the switching of power electronics devices are neglected to show the dynamic behavior of SOFC system for a long time.

The objective of this research is that a new control strategy based on adaptive control strategy is used to improve the dynamic response of FC systems. The proposed control strategy prevents SOFC system from overuse and underuse conditions. This control strategy is used to solve the problem of slow dynamic of SOFC system effectively and also to reduce the size of storage device which is connected to the DC link. Additionally, the effect of the proposed system on the dynamic behavior of the UF is investigated to indicate the validity of proposed system.

2. Methodology

In this section, the dynamic model of SOFC system and dynamic behavior of UF are presented. In first section, the dynamic model of SOFC system based on electrochemical equations is introduced. This model is current–voltage model of SOFC system. Voltage of SOFC system depends on amount of current drawn from SOFC system. In fact, based on current drawn from SOFC system the voltage can be calculated. With usage of these equations the

Table 1
Summary of SOFC system model.

Authors	Fuel cell model	Year	Contribution	Comments
Zhu and Tomsovic	Based on Padulles SOFC model 2	2001	Micro turbine helps load following performance	Fuel cell operates as a constant output power DG
Miao and Klein	Based on Padulles SOFC model	2002	Designed controllers to improve the oscillation damping of the whole system using linearzed model	Ignorance of incremental fuel cell output voltage. Average model of PCU
M.Y. El- Sharkh and A.K. Saha et al.	Based on Padulles SOFC model	2004 and 2007	In their proposed system PEMFC system are controlled based on traditional methods that are used for the control of active and reactive power output of a synchronous generator	It uses two proportional-integral controllers separately with FC system to control fuel flow. The two controllers are relative to each other
O.C. Onar et al.	Based on Padulles SOFC model	2006	The FC system is modified and integrated with the wind turbine generator, electrolizaer and storage model	In design of proposed model the authors did not consider the effect and behavior of FC system utilization factor under disturbance and the proposed model cannot show the exact behavior of FC system
M. Uzunoglu et al.	Based on Padulles SOFC model	2008	Hybrid power generation	In design of proposed model the authors did not consider the effect and behavior of FC system utilization factor under disturbance and the proposed model cannot show the exact behavior of FC system
M. Hoseintabar and M. Nayeripour and T. Niknam	Based on Padulles SOFC model	2010	1. The dynamic model of FC system is modified with considering the effect of utilization factor to operate in optimal value to enhance FC system performance and lifetime 2. Proposed model are investigated and are implemented with combination of SC system	
Proposed model	Based on Padulles SOFC model	2011	1. The dynamic response of FC system is improved with adaptive control strategy 2. Proposed model are investigated and are implemented with combination of SC system	

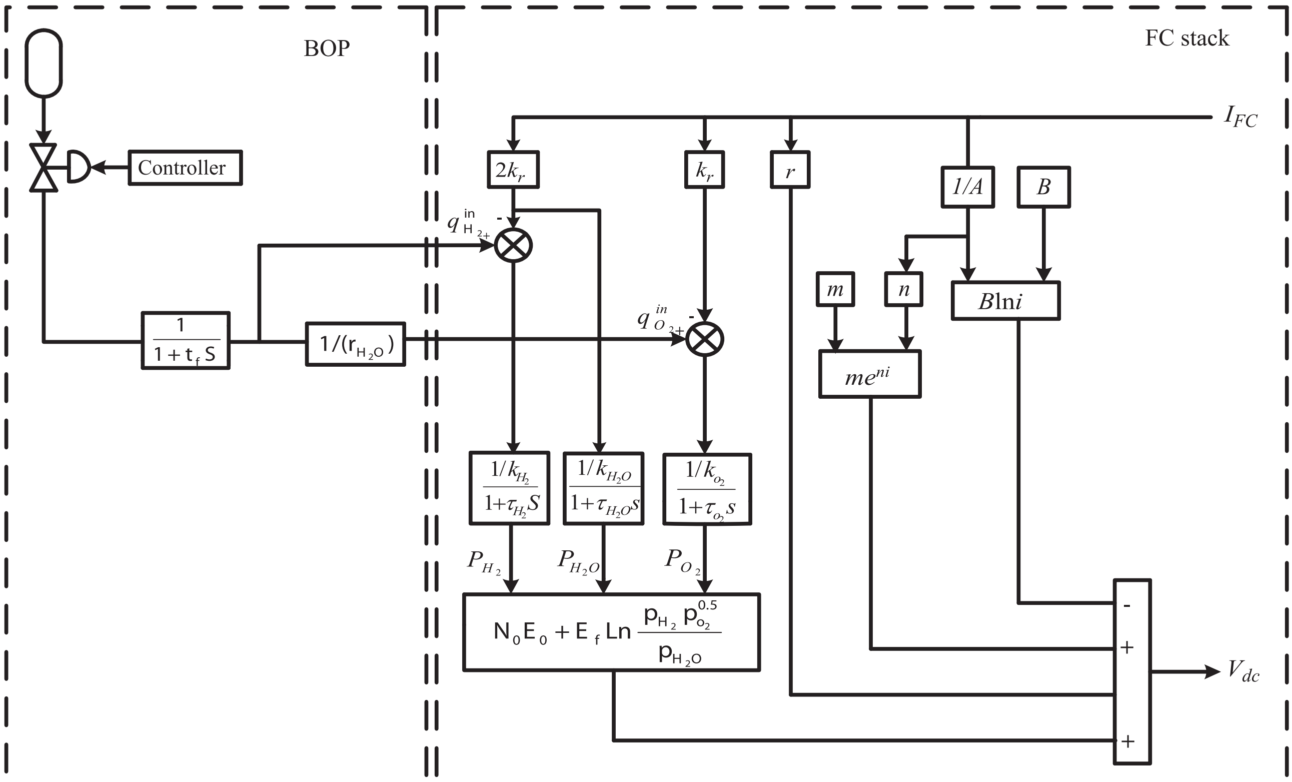

Fig. 1. SOFC system model.

voltage–current model of SOFC system is simulated. The block-diagram of Simulated SOFC system is shown in Fig. 1. In second section, the dynamic behavior of UF and the rule of this factor are presented.

2.1. SOFC dynamic model

Padulles et al. introduced a model for the SOFC power plant [12]. In this section, based on it and with considering of thermodynamic and electrochemical properties, a detail dynamic model of SOFC is used as showed in Fig. 1.

In this model, every individual and perfect gas will be verified and will be formulated separately, and so each gas (i.e. hydrogen) will be investigated as follows [13–16]:

Every individual gas will be verified separately, so the perfect gas equation will be applied to it, hydrogen will be considered as follows:

$$P_{H_2} V_{an} = n_{H_2} RT \tag{1}$$

Take the time derivative of the previous expression, obtaining:

$$\frac{dP_{H_2}}{dt} = \frac{RT}{V_{an}} q_{H_2} \tag{2}$$

$$\frac{dP_{H_2}}{dt} = \frac{RT}{V_{an}} (q^{in}_{H_2} - q^{O}_{H_2} - q^{r}_{H_2}) \tag{3}$$

According to basic electrochemical relationships between the molar flows of hydrogen that reacts can be calculated as follows:

$$q^{r}_{H_2} = \frac{N_0 I}{2F} = 2K_r I^{r}_{fc} \tag{4}$$

The hydrogen partial pressure can be rewritten as follows:

$$\frac{dP_{H_2}}{dt} = \frac{RT}{V_{an}} (q^{in}_{H_2} - q^{O}_{H_2} - 2K_r I^{r}_{fc}) \tag{5}$$

The molar flow of any gas (hydrogen) through the valve is proportional to its partial pressure inside the channel and can be express as:

$$\frac{q_{H_2}}{p_{H_2}} = \frac{K_{an}}{\sqrt{M_{H_2}}} = K_{H_2} \tag{6}$$

Using 1 and 2 taking Laplace transform the hydrogen partial pressure could be written as follows:

$$P_{H_2} = \frac{1/k_{H_2}}{1+\tau_{H_2} s} (q^{in}_{H_2} - 2K_r I^{r}_{fc}) \tag{7}$$

where

$$\tau_{H_2} = \frac{V_{an}}{RT\, K_{H_2}} \tag{8}$$

By using Nernst equation and ohms law, (to consider ohmic losses) the stack output voltage maybe expressed as:

$$V = N_0 \left(E_0 + \frac{RT}{2F} \left[\mathrm{Ln} \left(\frac{p_{H_2} p_{o_2}^{0.5}}{p_{H_2O}} \right) \right] \right) - r I^{r}_{fc} \tag{9}$$

The SOFC system model parameters used in this paper are shown in Table 2.

Table 2
The parameters of dynamic model of SOFC system.

Parameter	Representation	Value
T	Absolute temperature	1273 K
F	Faradays constant	96487 C/mol
R	Universal gas constant	8314 J/(kmol K)
E_0	Ideal standard potential	1.18 V
N_0	Number of cells in series in the stack	450
K_r	Constant, ($K_r = N_0/4F$)	9.9498×10^{-7} kmol/(S A) QUOTE QUOTE
U_{max}	Maximum fuel utilization	0.9
U_{min}	Minimum fuel utilization	0.7
U_{opt}	Optimal fuel utilization	0.8
K_{H_2}	Hydrogen valve constant	8.43×10^{-4} kmol/(S atm)
K_{H_2O}	Water valve constant	2.81×10^{-4} kmol/(S atm)
K_{O_2}	Oxygen valve constant	2.52×10^{-3} kmol/(S atm)
τ_{H_2}	Hydrogen time constant	26.1 s
τ_{H_2O}	Water time constant	78.3 s
τ_{O_2}	Oxygen time constant	2.91 s
R	Ohmic loss	0.126 Ω
T_e	Electrical response time	0.8 s
T_f	Fuel processor response time	5 s
r_{H-O}	Ratio of hydrogen to oxygen	1.145 s
N_s	Number of stacks	1

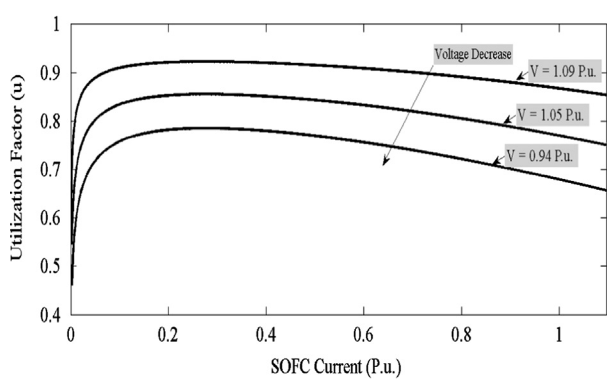

Fig. 2. The dynamic behavior of utilization factor.

2.2. Concept and dynamic behavior of the UF

One of the major variables that may affect the dynamic behavior and lifetime of the FC is the UF. In transient conditions, coordination between input and output flow rates of hydrogen because of different dynamic behavior of operating variables is highly important. The UF is defined as [16]:

$$u = (q_{H_2}^{in} - q_{H_2}^{o})/q_{H_2}^{in}$$

Under steady state conditions (when $t\to\infty$ and $s\to0$), the relationship between the UF, V_{dc}, and I_{FC} can be achieved as follows [16]:

$$\left(\frac{1}{u}-1\right)^2\left(\frac{2}{u}-r_{H-O}\right) = \frac{\exp\left(4F(V_{dc}-N_0E_0)/N_0RT - 2\mathrm{Ln}\left(\frac{K_{H_2O}}{K_{H_2}}\left(\frac{K_r}{r_{H-O}\times K_{O_2}}\right) + 4FI_{FC}r/N_0RT\right)\right.}{I_{FC}}$$

Fig. 2 is drawn based on SOFC data that are given in Table 2. Fig. 2 shows the dynamic behavior of the UF. As shown, the dynamic behavior and FC system variables are extremely changed by changing the load demands.

3. Power conditioning unit model

Fig. 3 shows a schematic diagram of the FC power plant interconnected to the load demand in stand-alone application. The FC system current is controlled by means of hysteresis current control through unidirectional converter. The storage device is always connected to the DC bus through a bidirectional DC/DC converter. The produced power of the storage system can be positive or negative, which allows energy to be transferred in both directions [6]. The storage device captures power in positive sudden step load and recaptures power in negative step load due to slow dynamic of the FC system [13–15].

The overall system configuration can be divided into three sections; power system, power condition unit and load demand. In power system section, FC and storage device supply the required power for load demand. In fact, the load demand have specific characteristics due to these reason power electronic devices with proper control strategy should be used. Different types of power electronics devices have been used in previous work [17,18]. In this paper, unidirectional converter with current controller is used. The objectives of selecting this kind of structure are that the power of FC system should be drawn from FC system and cannot be injected to FC system and also every kind of current controller DC/DC converter with different configuration can be implemented because the control strategy of power electronic devices is based on current control. In this case, the switching pattern of power condition unit can be made by desired reference current.

The storage device which is used in this paper as back-up system has two important rules.

1. Due to SOFC system constraints, the SOFC system cannot supply load demand in transient events such as step load demand. In this condition, storage devices such as battery bank or super capacitor are used to satisfy load demand completely.

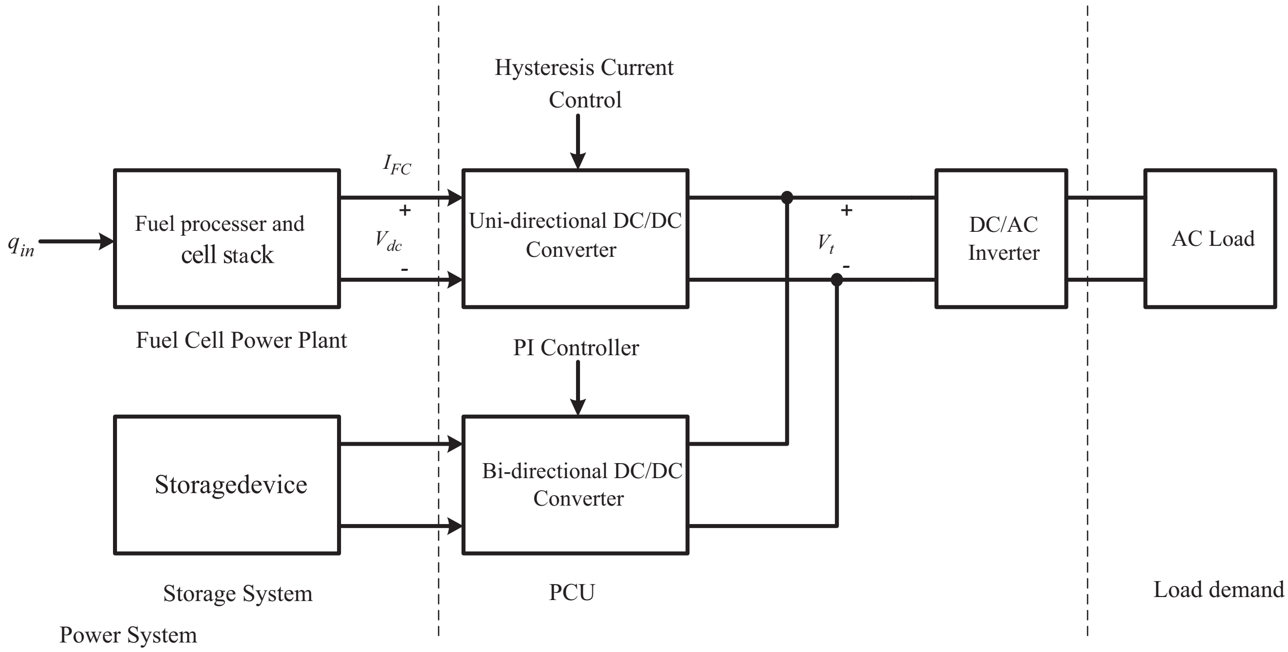

Fig. 3. The overall system configuration.

2. In fact, storage device with the aim of bi-directional converter set the voltage of DC link in constant value. The detail control strategy is investigated in our previous work [5].

The important issue about this control strategy is that the proposed control strategy can reduce the size of battery bank and overall cost.

4. Control strategy

In the studied distributed generation (DG) system, the variables that contain power generation and constraints should be controlled properly to improve FC system dynamic response. To achieve this goal, variables should be controlled by coordination between the input reference power to the power electronics interfacing and the UF. The appropriate control of the utilization factor can improve the performance and dynamic response of the FC system. The utilization factor of the FC system has to be kept in its allowable range ($0.7 < u < 0.9$) to protect the FC system from fuel starvation, unexpectedly high cell voltages and permanent damage [16].

In dynamic and transient interval consideration the affect and variation of temperature can be neglected because the variation of temperate need more time than the load demand variation [1]. This Paper emphasizes on short time interval. In addition, the proposed method does not have any restriction regarding the consideration of temperature, which is assumed to be constant in our paper. This model which is used in this paper has been implemented in dynamic description of SOFC system in pervious works [5,6,8,16].

For the safe operation of the FC system, the system′s UF has to be kept between over-used and under-used conditions ($0.7 < u < 0.9$). Thus, the excess ratio of hydrogen fuel flow needs to be adjusted rapidly by increasing and decreasing the mass flow rate into the FC stack, respectively. The dynamic response of the FC system due to the variation of hydrogen fuel flow is limited by the inertia (dynamic response) of the actuators. Over-used and under-used conditions of hydrogen fuel flow could occur, especially at fast load changes. The UF of FC system can be controlled by limiting the dynamics response of load changes. This control strategy reduces dynamic response of the FC system.

This paper proposes a new control strategy based on the adaptive control strategy, where the hydrogen fuel flow becomes a controllable variable. The proposed control strategy enhances FC system dynamic response and can also keep the UF of the FC system in its allowable range.

A proper controller for SOFC enabling them to supply step load variation rapidly by changing input fuel flow rate is proposed in this paper. The proposed control strategy forces the SOFC stack to respond to load changes rapidly by considering the stack operating limits. A proper reference current will not only satisfy the power demand in the minimum amount time, but can also keep the UF in its allowable range. To achieve this goal, three actuators should be considered; the valve, the mass flow controller, and the electrical load.

4.1. Control of fuel flow to the stack

In the steady state, the input hydrogen fuel flow is proportional to the stack current. Thus, the SOFC stack is operated with a constant steady-state UF by controlling the hydrogen fuel flow input to the stack according to $(2k_r/u_s)$ where u_s is the optimal utilization factor in steady state. To solve the slow dynamic of the FC system in transient events such as step load, a good control strategy is needed to enhance the slow dynamic of the FC system. The proposed control strategy in the literature operates desirably in steady state condition. However, because of FC system constraints, this control strategy cannot respond to variations of load demand power as fast as desired.

4.2. Control of power electronic interfacing

The FC systems are static power generations that produce DC power from electrochemical reactions. To satisfy AC load demand, the power produced by the FC stack has to be converted to an AC form by using power electronics interfacing. In recent years, different power condition units for the FC power generation system are proposed.

The hysteresis current controller is used to control the DC/DC converter of FC system. The desired power is produced by considering SOFC system constraints and can be controlled by power electronic interfacing. The objective of hysteresis current controller is to keep the actual value of the current within their hysteresis bands all the time. Two hysteresis bands with the width of (α) are used around reference value. The actual value of the current has to be kept within the hysteresis band. Each time when the current touches the lower or upper hysteresis band, the converter has to be switched in order to force the current to be in its allowable range.

Fig. 4 shows an overall system configuration of the FC power plant in stand-alone application. In this paper, the simplified model of power electronics interfacing components are considered and also the effects of ripples generated due to the switching of power electronics devices are neglected to show the dynamic behavior of SOFC system for a long time. The generated ripples due to switching of power electronics components can be reduced to desired levels by using filters on both the DC and AC sides and also by increasing the switching frequency of the power electronics interfacing devices [16]. Furthermore, the ripple does not affect the transfer of real power, which is the purpose of this paper. The losses in the switching devices are neglected.

4.3. Adaptive control strategy

To improve the operating performance of the dynamic response of the FC system power plant, a new control strategy according to adaptive control is employed to solve the slow

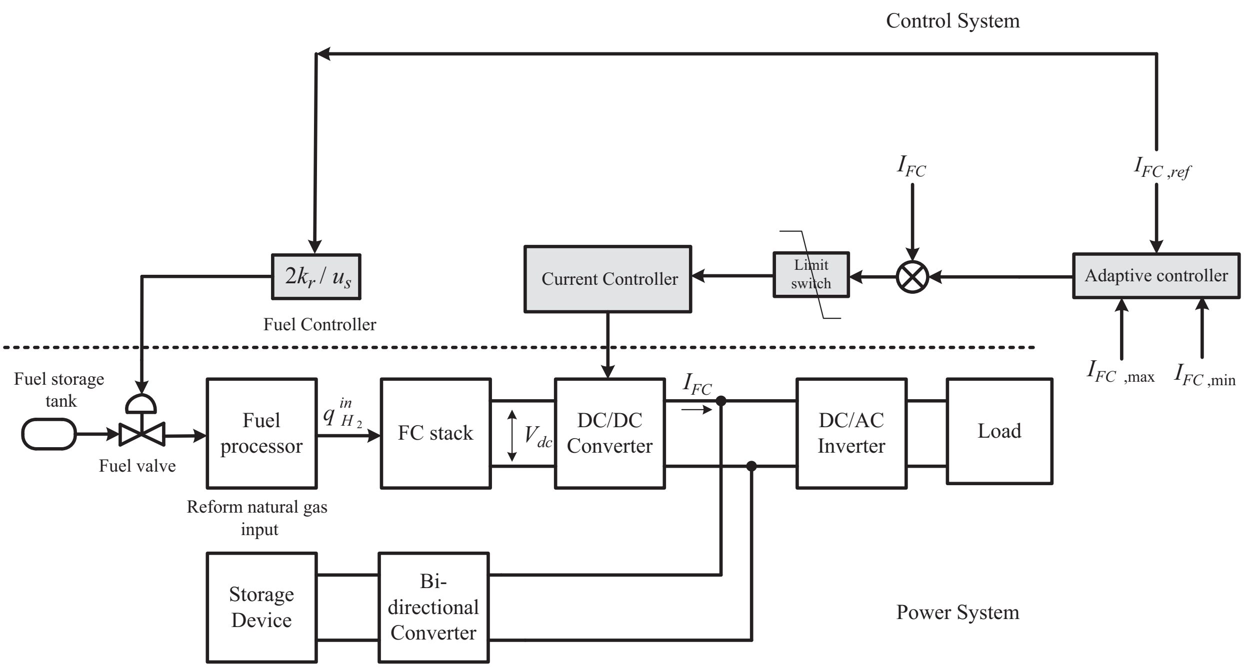

Fig. 4. Overall system configuration.

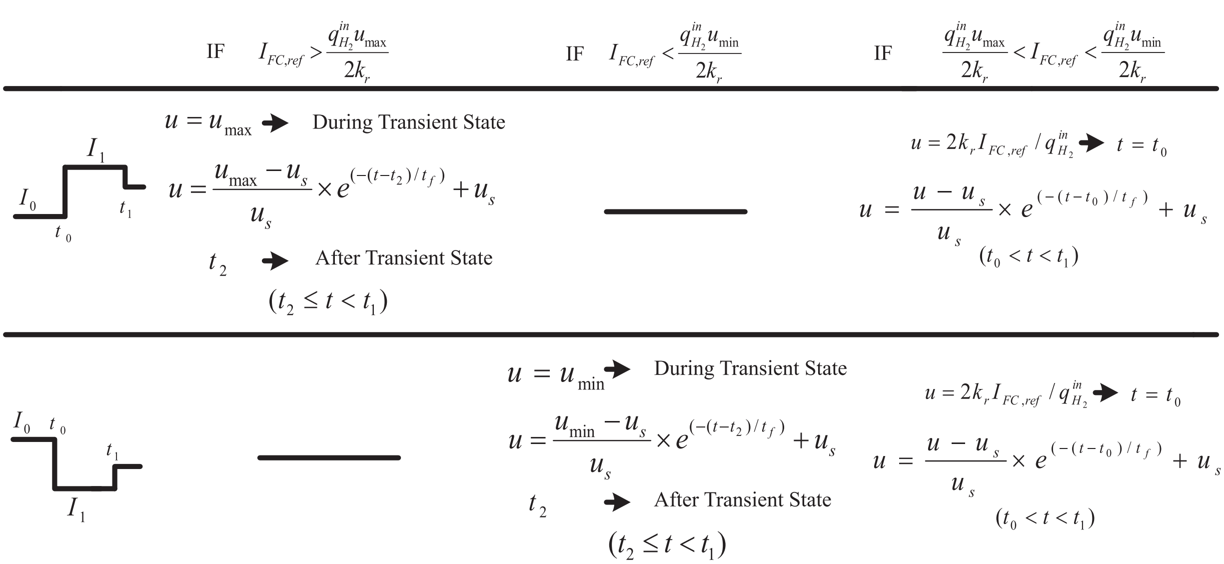

Fig. 5. Generality of the proposed adaptive control strategy.

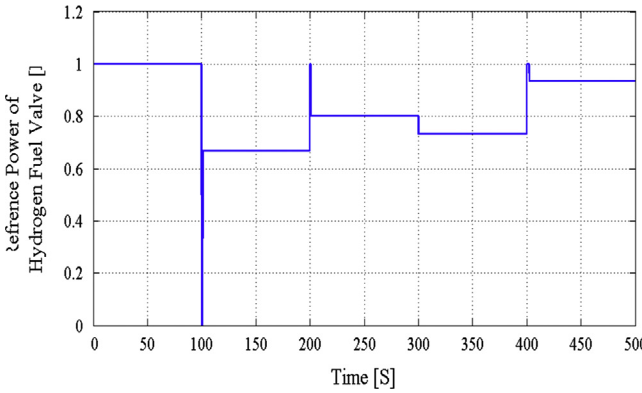

Fig. 6. Modified reference power.

dynamic of the FC system. This strategy, illustrated in Fig. 4, includes the adaptive control strategy based on coordination between power electronic devices and the UF.

The proposed adaptive control strategy adjusts the reference current of hydrogen fuel valve according to the level of the UF. The proposed control strategy sets the utilization factor of the FC system at its allowable ranges to protect and enhance its lift time. In the proposed control strategy, whenever the system is under positive or negative step load, the FC system can change its power as fast as desired if the variation of the UF is in its allowable range. However, if the variation of FC system is not in its allowable range, the adaptive control strategy changes the input signal of the fuel valve controller based on the maximum and the minimum power that can be drawn from the FC system. After passing the transient state and compensating the slow dynamic of the FC system, it will operate in steady state. Fig. 5 demonstrates the generality of the adaptive control strategy.

The objective of this control strategy is that the space of allowable range of UF should be used properly. Actually, when the positive step load demand applied to the proposed system, the reference power applied to the system is kept at its maximum value until the power of SOFC system reach to its desired value. Also, when the negative step load demand applied to the proposed system, the reference power applied to the system is kept at its minimum value until the power of SOFC system reach to its desired value. The variation of UF with this control strategy is shown in Fig. 5.

In positive step load demand, with this control strategy, when the produced power is more than the reference power the UF receives its maximum value. The time interval which the UF receive its maximum value increases in this control strategy. The dynamic behavior of hydrogen fuel valve defines the dynamic behavior of UF. When the produced power of SOFC equal to load demand the reference power return to its actual value. In this time the UF gradually receive its optimal value.

In negative step load demand, with this control strategy, when the produced power is lower than the reference power the UF receives its minimum value. The time interval which the UF receive its minimum value increases in this control strategy. When the produced power of SOFC equal to load demand the reference power return to its actual value. Therefore, the UF gradually receive its optimal value. The modified reference power which is applied to the system is shown in Fig. 6.

5. Results

In order to verify the system performance under different situations, simulation studies have been carried out by using different step load demand. As discussed in Section 3, the system is implemented to supply the load demand in a standalone application.

The simulation results in this section are used to illustrate how SOFC power plant can be controlled in the stand-alone condition to change its output power level through the control scheme discussed in Sections 3 and 4. The simulation results are based on the 100-kW SOFC plant data given in Table 2.

The validity of the proposed control strategy is investigated through simulation by using the nonlinear model shown in Fig. 1. The simulation tool that is used to verify the proposed control strategy is MATLAB/SIMULINK. The proposed control strategy is simulated for 500 s to demonstrate the transient response of the SOFC system in stand-alone application during both the increase and decrease of real power. The step load demand is connected to proposed hybrid system to investigate the dynamic behavior of proposed controller precisely. Step load used in this system have two kind of steps; negative step and positive step. To show the effective of this system the variation of the large step and small step are applied to the system. The purpose of this selection is to show that in small step load the proposed control strategy completely can satisfy power of load demand and in large step load (negative or positive) the dynamic response of SOFC is enhanced. Also, the variations of load demand have more effect in step load against the ramp load demand. Therefore, in this paper the worst condition of this variation (step load) has been investigated to show the effectiveness of this control strategy. In fact, we have better condition in ramp load demand.

This section presents four cases (steps of real power) for studying dynamic respond performance of the proposed adaptive control strategy. Fig. 7 shows the dynamic simulated responses of the proposed adaptive control strategy whose simulation results under various operating conditions are analyzed in this section, respectively. Without restricting the step magnitude of load demand Ref. [19], the output power variation of SOFC system is attempted to be met by a step change in load demand instantaneously. Although the output real power of the SOFC system can be change instantaneously and satisfy the load demand completely (black line) as shown in Fig. 7, the UF is not restricted to the allowable region during the transient state. Therefore, this model is not suitable to be used in a transient state and does not have any control strategy for restricting the slope of the SOFC system power and this will damage the SOFC. In Ref. [5] (red line), the authors proposed a new control strategy for improving SOFC system lifetime. Keeping the UF in its optimal value is the objective of their work. The main drawback of this work is its slow dynamics. In Ref. [6] which is shown in Fig. 6 as green line, the normal operation of SOFC system is shown. The UF varies in its allowable rang and the power drawn is restricted. In fact, according to Fig. 5, the maximum safe step size is appropriate with the initial power level of load demand. Therefore, power can only have a specific maximum safe step when the step load demand happens.

In order to prevent the SOFC over-used and under-used conditions, the SOFC output power slope should be controlled properly. In Ref. [12], the authors introduced the SOFC system model that is used as the basic model in recent years. In their model the output power of the SOFC system is controlled base on limited switch. However, the dynamic response of the SOFC system is too slow and the duration of the transient state is not proper. One of the main problems that the users have with the usage of FC system is the dynamic response of the SOFC system in a transient state.

In Ref. [5], the authors proposed a new simplified control strategy based on coordination between the SOFC system and power electronics devices to enhance the FC system lifetime and performance. The UF of the SOFC system in the proposed control strategy operates in its optimal value (u=0.8). However, the dynamic response of the SOFC system is too slow.

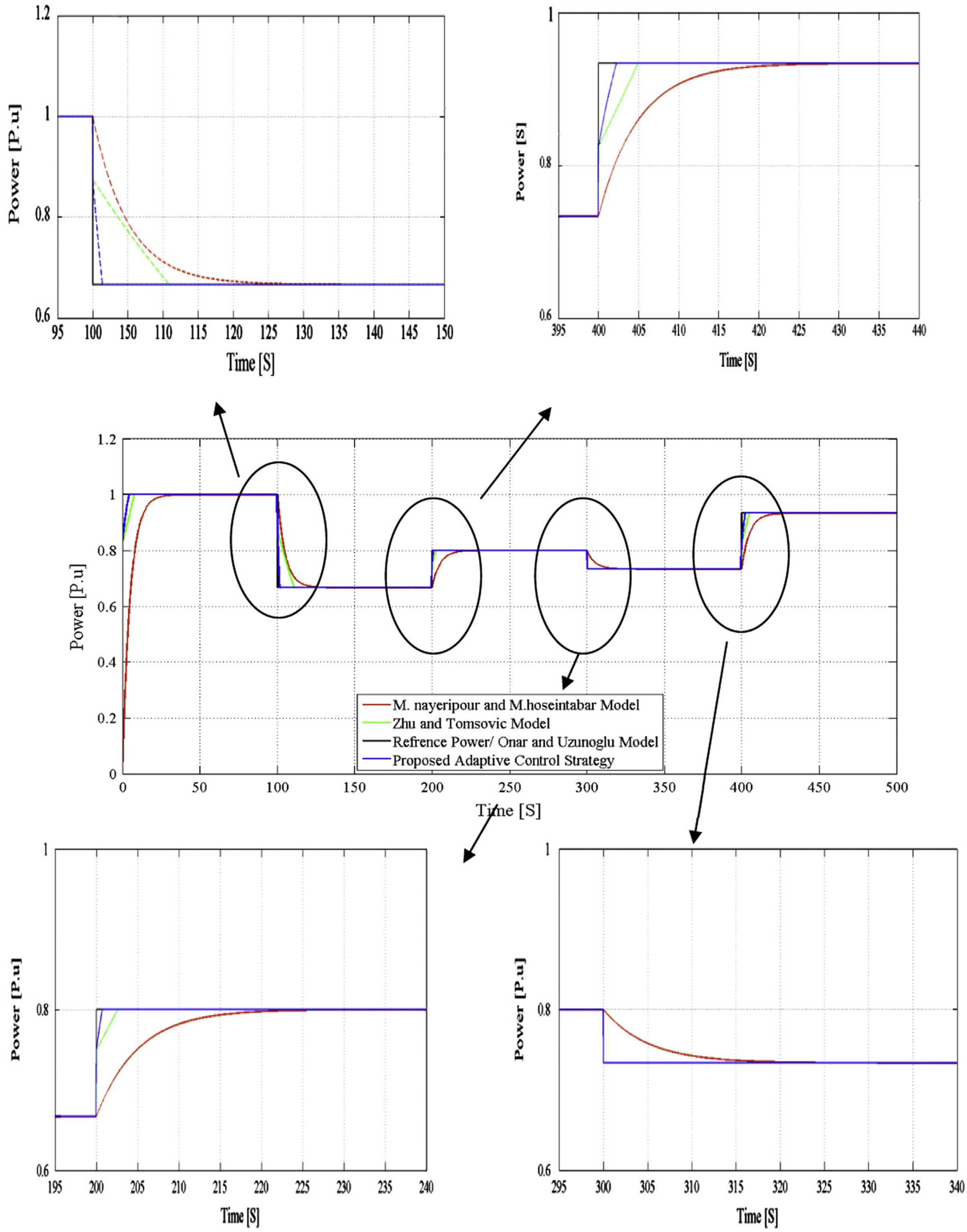

Fig. 7. Produced power of SOFC system.

A novel adaptive control strategy is proposed. The main core of this proposed control strategy is based on an optimal usage of the utilization factor′s allowable region. To improve the dynamic response of the SOFC system under transient state, the hydrogen fuel valve is controlled by the value of the UF. The hydrogen fuel valve and the air valve depend on each other with a constant factor. The applied signals to the hydrogen and oxygen fuel valve are controlled and are operated between the maximum and minimum value. In step load, the dynamic behavior of the UF in the proposed model is simulated and is calculated.

It is seen that u remains within the allowable range during the transient state. From Fig. 8, it is clear that u remains on its limit of u_{max} or u_{min} until the SOFC reaches the target power and also the dynamic response of the proposed control strategy is compared with the previous works. Simulation results show that the adaptive control strategy is able to improve the dynamic response of

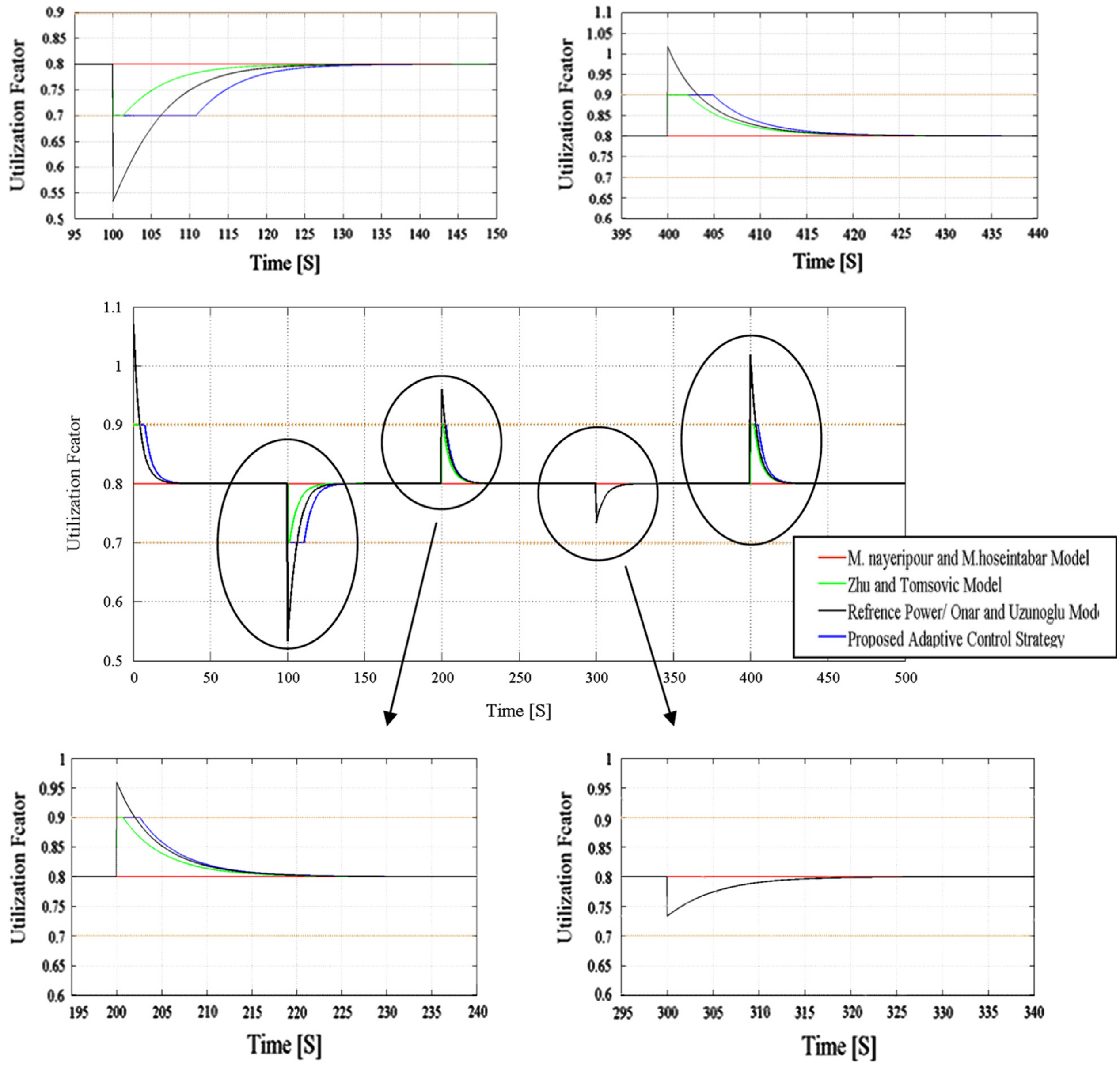

Fig. 8. The dynamic simulated responses of the utilization factor.

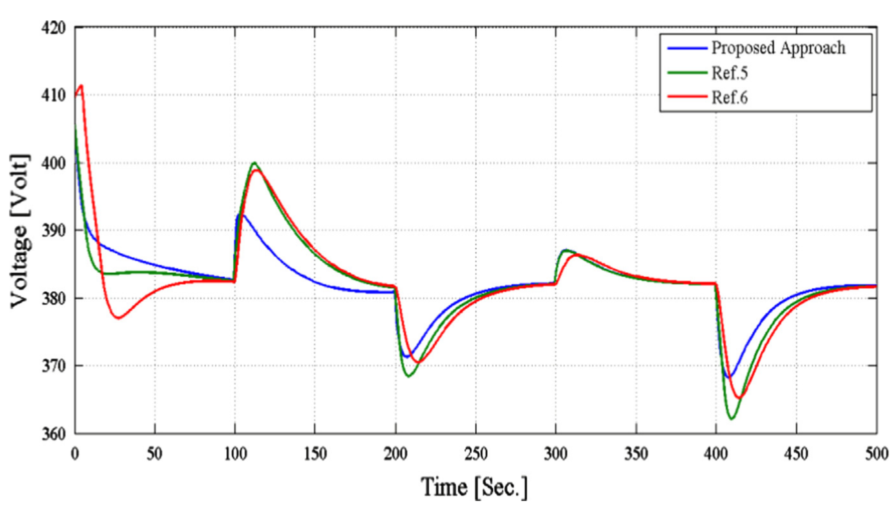

Fig. 9. The variation of SOFC voltage.

the FC system performance, and appropriately distribute the electrical power between the fuel cell and the storage devices.

The variation of power and current are like to each other because the power which is drawn from SOFC system is based on current. The voltage of SOFC system is related to the current which is drawn from SOFC system due to this reason, the variation of voltage is simulated and shown in Fig. 9.

6. Conclusion

This paper proposes a dynamic control strategy model for the solid oxide fuel cells based on adaptive control. This strategy can be implemented on any other applications. Simulation results show that the proposed adaptive control strategy has better transient responses than the previous controllers that are used under load variations. The proposed controller has also demonstrated its advantage to deal with the operation of the SOFC with constraints. The results are compared with those of a previous model which has been proposed in previous literature to show the validity and the effectiveness of this control strategy.

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